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Analysis of the Acid-Base Balance in Arterial Blood Plasma of Elderly Patients

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ABSTRACT

We have previously found that in the normal blood, where a metabolic component of pH, pH°, was ignored, a respiratory component, pH*, was given by a linear logarithmic function of P_{CO_2},; pH° was then obtained by subtracting pH* from the measured value for pH. Analysis of the acid-base imbalance was greatly facilitated by this division of pH into its metabolic and respiratory components. In arterial blood of elderly patients, the regression functions of pH and pH* against pH° were linear. P_{CO_2} was also linearly related to pH°, whereas pH* showed a reciprocal relation to pH°. It was then established that about 26% of pH° was compensated for by the change in pH*, so the change in pH was limited to 74% of the change in pH°. Since pH is the sum of pH* and pH°, the deviations of the individual points of pH and pH* from the respective regression lines became equal. Designating the pH and pH* values on the respective regression lines by $\overline{\mathrm{pH}}$ and $\overline{\mathrm{pH}}$*, pH $-$ $\overline{\mathrm{pH}}$ became equal to pH* $-$ $\overline{\mathrm{pH}}$*, because pH $-$ pH* $=$ $\overline{\mathrm{pH}}$ $-$ $\overline{\mathrm{pH}}$*.

Key words : Henderson equation, Regression analysis, Correlation ratio, Metabolic P_{CO_2} change, Ventilation/Perfusion ratio.

INTRODUCTION

pH in blood plasma is determined by P_{CO_2} and $[HCO_3^-]$ according to the Henderson equation[1]. As described previously, we found that at steady state *in vivo* both pH and $[HCO_3^-]$ had a P_{CO_2}-dependent respiratory component and a metabolic component[1),2),3)]. The respiartory component of $[HCO_3^-]$, designated by $[HCO_3^-]$*, was given by an exponential equation of P_{CO_2}. The P_{CO_2}-depend-

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ent component of pH, pH*, was given by setting $[HCO_3^-]^*$ in the Henderson equation by a linear logarithmic function of P_{CO_2}. The metabolic component of $[HCO_3^-]$, $[HCO_3^-]^\circ$, was obtained by subtracting $[HCO_3^-]^*$ from the measured value for $[HCO_3^-]$. Similarly, the metabolic component of pH, pH°, was obtained by subtracting pH* from the measured pH value. Thus, it has become possible to analyse the acid-base imbalance in blood plasma by dividing pH into pH* and pH°. When pH° deviates from its normal level, close to zero, not only pH, but also P_{CO_2} changes in proportion to the change in pH°. Despite the wide scattering in the measured P_{CO_2} values, the ratio of the change in pH* to pH° has been assessed by regression analysis in a number of elderly patients.

According to the Henderson equation, pH° is given by a logarithmic function of the ratio $[HCO_3^-]^\circ/[HCO_3^-]^*$, irrespective of P_{CO_2}[3]. Moreover, since P_{CO_2} and pH* showed a Gaussian distribution around their regression lines, the mean ratios of pH and pH* to pH° were given by their respective correlation ratios against pH°. The extent of the imbalance has long been recognized by the change in $[HCO_3^-]$ from the normal value. Since $[HCO_3^-]$ is not linearly related to pH, it has been difficult to evaluate the change in P_{CO_2} connected with the metabolic change in pH. However, the present paper shows the regression functions of pH and pH* are linear against pH°, and the mean ratios can be calculated from the correlation ratios. The correlation ratio of pH* to pH° in arterial blood of elderly parients was about −26% and that of the measured pH to pH° was 74%. Furthermore, the deviations of individual values of pH* and pH from the respective regression functions are equal. Designating values for pH* and pH on the regression lines by $\overline{pH}^*$ and $\overline{pH}$, the difference $\overline{pH}-\overline{pH}^*$ also becomes equal to pH°

METHODS AND RESULTS

All the correlations of pH and pH* against pH° were calculated on arterial blood sampled from 215 elderly patients (Table 1). The blood samples were obtained with consent of all the patients. The numbers of male and female patients were 77 and 138, respectively, and their ages ranged from 64 to 97. The mean ± SD of the age of male patients was 82.8 ± 7.4 and that of the female patients was 83.6 ± 6.6. Summarized data for pH, P_{CO_2}, $[HCO_3^-]$ and other relevant parameters (n=278) are shown in Table 1. pH and P_{CO_2} were measured using a blood gas analyser (Ciba Corning 188). $[HCO_3^-]$ was calculated from $[H^+]$ and P_{CO_2} using the Henderson equation[1,4]. pH* was calculated by setting P_{CO_2} into the following equation[1]:

$$pH^* = 8.285 - 0.543 \log P_{CO_2}. \quad (1)$$

pH° was obtained by subtracting pH* from the measured value for pH. To confirm the validity of pH°, $[HCO_3^-]^*$ was calculated according to the following equation:

$$[HCO_3^-]^* = 4.717\, P_{CO_2}^{\,0.457}, \text{ (mEq)}. \quad (2)$$

$[HCO_3^-]^\circ$ was obtained by subtracting $[HCO_3^-]^*$ from the measured value of $[HCO_3^-]$. Further, since pH° is given by the following equation[3]:

$$pH^\circ = pH - pH^* = \log(1 + [HCO_3^-]^\circ/[HCO_3^-]^*), \quad (3)$$

Table 1. Summarized data for pH, Pco_2, $[HCO_3^-]$ and other relevant parameters in arterial blood sampled from 215 acidotic, normal and alkalotic elderly patients.

	Acidotic group $pH^o < -0.02$		Normal pH group $-0.02 < pH^o < 0.02$		Alkalotic group $pH^o > 0.02$	
Samples and patients						
	male	female	male	female	male	female
No of samples	18	38	33	53	56	80
No of subjects	18	38	27	44	32	56
Mean age ± SD	81.3 ± 6.9	83.6 ± 6.9	84.9 ± 7.6	84.2 ± 7.2	82.0 ± 7.6	83.1 ± 5.9
Parameters obtained						
pH	7.404 ± 0.044		7.442 ± 0.030		7.480 ± 0.040	
Pco_2	34.33 ± 4.57		36.29 ± 4.23		39.28 ± 5.19	
$[HCO_3^-]$	21.30 ± 2.29		24.44 ± 1.30		28.94 ± 3.06	
$[HCO_3^-]$*	23.67 ± 1.47		24.30 ± 1.31		25.19 ± 1.53	
pH*	7.453 ± 0.033		7.440 ± 0.028		7.422 ± 0.032	
pH^o	−0.050 ± 0.035		0.002 ± 0.010		0.059 ± 0.032	

the validity of pH^o was readily reconfirmed.

Values for pH^o (pH−pH*) were distributed from −0.16 to 0.14. The values fell into three groups: an acidotic group (56 samples), where pH^o was less than −0.02, an alkalotic group (136 samples), where pH^o was greater than 0.02 and a normal group (86 samples). Over 50% of the measured pH values were alkalotic, whereas about 20% were acidotic.

In the alkalotic group the mean Pco_2 was higher and the mean pH* was lower than in the other groups, indicating that the change in pH* was opposite in sign to that of pH^o = pH−pH*.

Correlations of pH and pH* against pH^o

The correlation coefficient and the regression function were calculated using Kaleid Graph Software (Synergy). Fig. 1 shows pH−7.4 plotted against pH^o in arterial blood sampled from the elderly patients shown in Table 1. The correlation coefficient was 0.78 and the regression function ($\overline{pH}$) was linear as shown by the interrupted line. The change in pH was about 74% of pH^o as shown by the following equation:

$$\overline{pH} = 7.439 + 0.74\, pH^o. \tag{4}$$

The mean ± SD of the deviation of individual points for pH from the regression line pH was 0.01 ± 0.030.

In Fig. 2, pH*−7.4 is plotted against pH^o. The correlation coefficient was 0.39 and the regression function ($\overline{pH^*}$) shown by the interrupted line was linear as follows:

$$\overline{pH^*} = 7.439 - 0.26\, pH^o. \tag{5}$$

From Eqs. (4) and (5), it is seen that about 26% of the change in pH^o was compensated for by the change in pH*. From the definition of pH^o the following equation was derived:

$$pH^o = pH - pH^*. \tag{6}$$

From Eqs. (4), (5) and (6) the following equation was then obtained:

$$pH - pH^* = \overline{pH} - \overline{pH^*} = pH^\circ. \quad (7)$$

Eq. (7) states that the deviation of pH from its regression line, i.e., $pH - \overline{pH}$ always equals the deviation of pH* from its regression line, i.e., $pH^* - \overline{pH}^*$.

Figure 3 shows the correlation of P_{CO_2} against pH°, where the correlation coefficient was 0.402. The regression function ($\overline{P_{CO_2}}$) was approximately given by the following linear equation:

$$\overline{P_{CO_2}} = 36.48 + 40.3\ pH^\circ, \text{(mmHg)}. \quad (8)$$

The mean ± SD of the deviation of individual points of P_{CO_2} from P_{CO_2} was 0.15 ± 4.71 mmHg.

Correlations of $[HCO_3^-]^\circ$ and $[HCO_3^-]^*$ against pH°

The ratio $[HCO_3^-]/[HCO_3^-]^*$ at the same P_{CO_2} obtained from the Henderson equation is free from P_{CO_2}. Since pH° is given by $\log([HCO_3^-]/[HCO_3^-]^*$, as shown in Eq. (3), pH° also becomes free from P_{CO_2}. To demonstrate that pH° was independent of P_{CO_2}, the correlation of $[HCO_3^-]^\circ$ against pH° was calculated in the arterial blood. The interrupted line in Fig. 4 shows $[HCO_3^-]^\circ$ calculated from pH° using the following equation:

$$[HCO_3^-]^\circ = 24.63\ (\log^{-1} pH^\circ - 1), \text{(mEq)}, \quad (9)$$

24.63 mEq in the above equation is the mean value for $[HCO_3^-]^*$ in the arterial blood. All the measured values of $[HCO_3^-]^\circ$ were distributed closely round the theoretical value indicated by the interrupted line, suggesting that the relationship between pH° and $[HCO_3^-]^\circ$ was uninfluenced by P_{CO_2}. The thin dashed line in Fig. 4 indicates the change in $[HCO_3^-]^*$ calculated from P_{CO_2} given by Eq. (8). The magnitude of the change in $[HCO_3^-]^*$ was about 20% of that in $[HCO_3^-]^\circ$.

Figure 5 shows the changes in pH* and

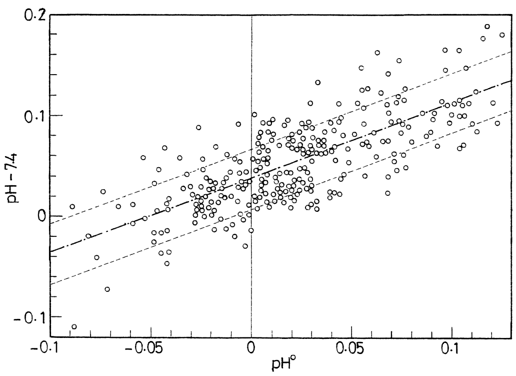

Fig. 1. pH−7.4 plotted against the metabolic component of pH (pH° = pH−pH*) in arterial blood of the elderly patients. The interrupted line is the regression line and the two dashed lines show the standard deviation of individual pH values from the regression line.

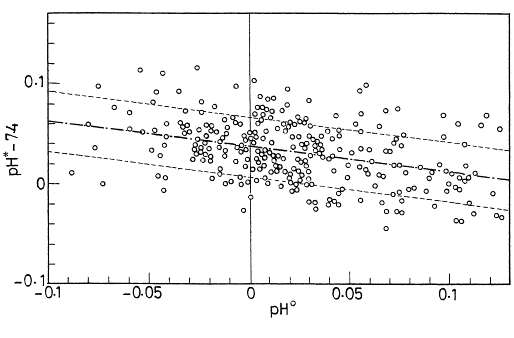

Fig. 2. pH*−7.4 plotted against pH° (pH−pH*) in arterial blood of the elderly patients. The interrupted line is the regression line and the two dashed lines show the standard deviation of individual pH* values from the regression line.

$[HCO_3^-]^*$ depicted against pH^o (lower abscissa) and $\overline{Pco_2}$ (upper abscissa), using Eqs. (2), (5) and (8). $[HCO_3^-]^*$ and $\overline{Pco_2}$ increased together with an increase in pH^o, while pH^* showed a reciprocal change to that in pH^o, demonstrating that the influence of pH^o on pH is reduced by the reciprocal change in pH^*. From this data the extent of the compensatory influence of pH^* was taken to be about 26%.

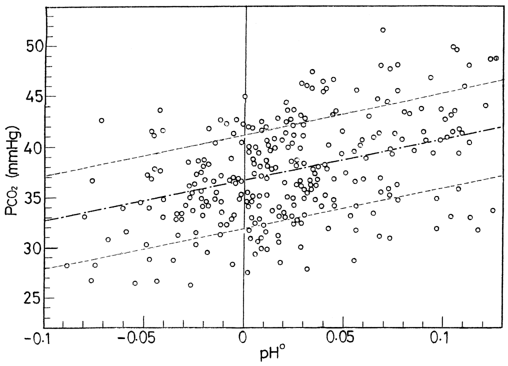

Fig. 3. Pco_2 plotted against pH^o in arterial blood of the elderly patients. The interrupted line is the regressione line and the two dashed lines show the standard deviation of individual Pco_2 values from the regression line.

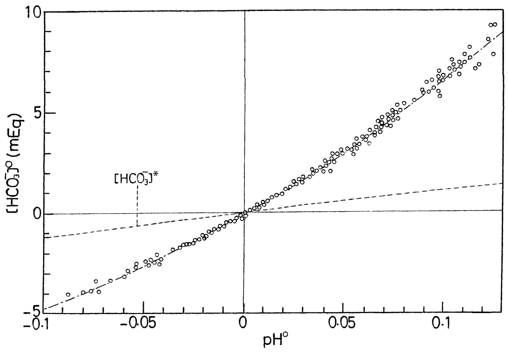

Fig. 4. $[HCO_3^-]^o$ plotted against pH^o. The interrupted line shows the theoretical value for $[HCO_3^-]^o$ = 24.63 ($\log^{-1}pH^o$ -1), 24.63 (mEq) being the mean value of $[HCO_3^-]^*$. The dashed line is the regression line of $[HCO_3^-]^*-24.41$ (mEq) against pH^o using the values derived from Eq. (8)

DISCUSSION

In the preceding paper[3] regression analyses of pH and Pco_2 in elderly patients were made against $[HCO_3^-]^o$, but not pH^o, to quantify the compensatory change of pH^*. However, since their regression functions were not linear, the correlation ratio of pH^* to pH^o could not readily be recognized. To derive a linear relationship between pH, pH^* and Pco_2, we attempted to calculate the regression functions of pH, pH^* and Pco_2 against pH^o in a number of the elderly patients. As shown in Figs. 1 and 2, pH and pH^* were linearly correlated against pH^o. The regression coefficient of pH against pH^o was 0.74 as given by Eq. (4) and that of pH^* was -0.26 as given by Eq. (5). Moreover, the regression function of Pco_2 against pH^o was also linear against pH^o as given by Eq. (8). By dividing pH into respiratory and metabolic components, an accurate measure of the acid-base imbalance could be obtained.

Generally, Pco_2 in arterial blood is controlled by respiratory factors, such as the ventilation/perfusion ratio or the Comroe ratio[5]. Figure 1

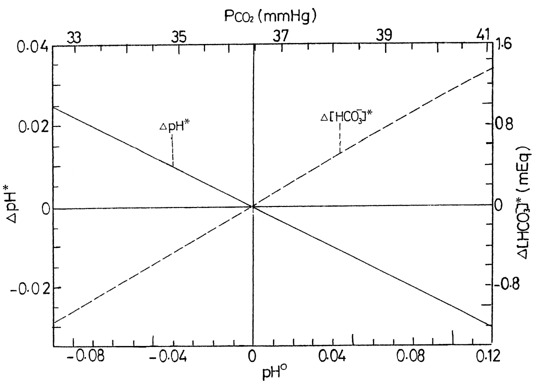

Fig. 5. $pH^*-7.439$ ($\triangle pH^*$) and $[HCO_3^-]^*-24.41$ ($\triangle[HCO_3^-]^*$, mEq) calculated against pH^o and Pco_2 by using Eqs. (2), (5) and (8).

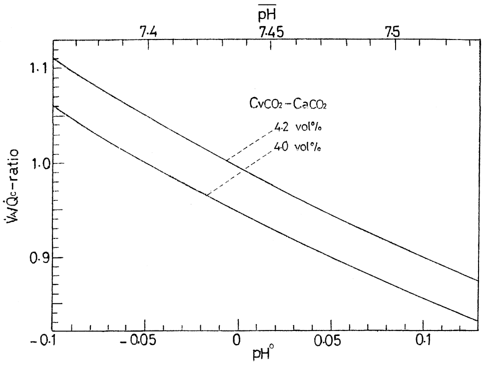

Fig. 6. The ventilation-perfusion ratio $\dot{V}_A/\dot{Q}_C$ calculated from Eq (10) by using P_{CO_2} on its the regression line against pH° given by Eq. (8). $\dot{V}_A$: alveolar ventilation volume (l/min) and $\dot{Q}c$: pulmonary blood flow (l/min).

shows that the mean pH value increased from 7.36 by 0.20, while in Fig.2 pH* decreased from 7.463 by −0.056, as pH° increased from −0.1 to 0.12. Taking into account that the magnitude of the change in pH° was much greater than that of pH* and that the change in pH* was reciprocal of that in pH°, the change in ventilation seemed to be initiated by the change in pH°, not in P_{CO_2}. In other words, the change in P_{CO_2} appears to be a result, not a cause of the change in ventilation.

Thus, setting P_{CO_2} on its regression line against pH° (Eq. (8) into the equation for the Comroe ratio[5], the effect of pH° on the pulmonary ventilation was calculated as follows:

$$\dot{V}_A/\dot{Q}_C = (Cv_{CO_2} - Ca_{CO_2})/(4.23 + 4.67\,pH^{\circ}). \quad (10)$$

(Cv_{CO_2} − Ca_{CO_2}) of Eq. (10) is the venous-arterial CO_2 difference (vol%). Figure 6 shows two curves for the $\dot{V}_A/\dot{Q}_C$ ratio against pH° (lower abscissa) and $\overline{pH}$ (upper abscissa). (Cv_{CO_2}−Ca_{CO_2}) in the upper and lower curves was taken to be respectively 4.2 and 4.0 vol%. The $\dot{V}_A/\dot{Q}_C$ ratio decreased hyperbolically as pH° increased.

As seen in Fig. 2, pH* showed a Gaussian distribution around its regression line against pH° and, as given by Eq. (5), the regression coefficient of pH* against pH° was −0.26. This suggests that the response of respiratory function to the change in pH° was identical among individual patients. Furthermore, because the change in pH* was reciprocal to that in pH°, and pH was the sum of pH° and pH*, the pH difference, pH−pH*, was always equal to $\overline{pH} - \overline{pH}^* = pH^{\circ}$, as given by Eq. (7). This seems to be attributable to the fact that P_{CO_2} or pH* was evenly distributed, among individual blood samples, around their respective regression functions against pH°.

Over-all, the analytical method of dividing pH and [HCO_3^-] into respiratory and metabolic components may help to obtain a presice information about the relationship between parameters related to the acid-base balance.

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